Plasma Heating by Charge Exchange Friction

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Abstract

Observations show that transverse heating and resultant outflow of ionospheric plasmas is highly correlated with DC electromagnetic energy flux into the ionosphere. This suggests a mechanism powered by the motion of plasmas through the neutral upper atmosphere, rather than by magnetic field-aligned current flow. The frictional interaction between plasma is closely related to the familiar ion pick up process at heights where the ions are nearly magnetized and dominated by charge exchange interactions with gas. At such heights, a phenomenon called "charge exchange friction" powers velocity space instabilities when the convective drift motion exceeds the neutral thermal speed. The result is a "ring-beam" or toroidal velocity distribution. These have been detected in the ionosphere by direct plasma measurements, inferred from observations of the associated waves, and inferred from the echo spectra of incoherent radar observations of rapidly convecting ionospheric regions. They are unstable to plasma wave growth, and the driven waves must be such as to thermalize the distributions, mainly via perpendicular energy diffusion when ion speeds are much less than the local Alfvén speed. Simple diffusive simulations yield exponential (in v) distributions with power law tails, as observed. The e-folding speed is double the local ion-neutral relative flow speed, as expected for ion

pickup. When this process acts along auroral magnetic field lines, the escape flux of ionospheric oxygen increases rapidly with Poynting flux in agreement with observations. Charge exchange friction is a universal plasma process that will produce ion acceleration and heating wherever fast plasma flows are driven through neutral gas.

Problem

Heating and ablation of ionospheric plasma by solar wind energy is an important atmospheric loss process that shapes Earth's magnetosphere during space storms, adding substantial plasma pressure to the magnetosphere [Moore and Horwitz, 2007]. The rate of removal of Earth's atmosphere is non-threatening over meaningful times scales, but is representative of a widely relevant space plasma process that played a role in removing much of the atmosphere of our nearest, but unmagnetized neighbor, Mars. It has long been thought that energetic auroral processes are responsible for this outflow. The most probable agent of such heating and acceleration was thought to be magnetic field-aligned electric currents that transmit stresses to the ionosphere. The heating would then be centered in the auroral acceleration region at about 1 R_E altitude. There is no doubt that energization in this altitude range is effective in raising the flow speed of ion outflows. On the other hand, the flux is most influenced by energy inputs at lower altitudes before the flows become supersonic.

Strangeway et al. [2005] and Zheng et al. [2005] found that two distinct magnetospheric factors are well correlated with outflow flux: i) the precipitating electron density and ii) the DC electromagnetic (or Poynting) flux into the F region ionosphere. Plasma outflow resulting from topside electron heating by soft electron precipitation is well understood and studied, e.g. Caton et al. [1998], Zeng et al., [2008]. Heavier ions are drawn out electrostatically by heated electrons, as is the photoelectric light ion polar wind but with greater force to lift heavy ions. These are also driven out of the ionosphere by wave energy dissipation and the pressure they acquire from the heating. However, it remains to understand the source of the active waves, especially at altitudes below the auroral acceleration region.

This paper describes a mechanism for the generation of the appropriate waves that is familiar in other contexts where ions and neutrals interact. This mechanism is distinct from dissipation of such currents in the lower parts of the ionosphere where ions are demagnetized by collisions, usually known as Joule or more properly as frictional heating. The focus here is instead the region where charge exchange collisions are the most important ion-neutral interaction. For that reason, we identify the relevant process as "charge exchange friction."

Charge Exchange Friction

Charge exchange friction works as follows: A plasma velocity space instability is intrinsic to a non-thermal feature of the ion velocity distribution, which is created by steady convection of ions through the neutral atmospheric gas, at altitudes where the plasma is marginally magnetized but subject to charge exchange interactions. This process is closely related to the "pick up" process that occurs within the interstellar gas flow throughout the solar system, which is greatly enhanced near localized gas sources such as un-magnetized planets, satellites, or comets. Pick up ions are low speed ions produced by photo-ionization of neutrals. Charge exchange ions {CEI} are slow speed ions produced when an electron is transferred from a fast ion to a slow neutral atom, with negligible momentum transfer. An ion with low velocity characteristic of the neutral gas thermal speed is picked up by the plasma convection via the electric field as seen in the neutral frame, gaining a gyration speed equal to double the speed of convection. The result is a ring or toroidal velocity distribution, rooted in the neutral frame and encircling the convecting plasma frame in velocity space.

The mechanism was studied in the 1970's, reviewed by St-Maurice and Schunk, [1979] and revisited by Barakat et al., [1983[. The velocity distributions that result are "ring beam" distributions, identical to those of the "ion pick up" process [Bogdan et al., 1991; Szegö et al., 2000], but with a different source of slow speed ions in the neutral gas frame. Charge exchange collisions have a large cross section and are effective in producing a slow ion and a fast neutral. Charge exchange friction is an fundamental aspect of any situation in which powerful moving driver plasma is magnetically linked to plasmas immersed within an "anchor" gas.

Centrifugal Acceleration

Terrestrial ionospheric F-region convection is much slower than solar wind speeds, owing to the large ratio of magnetic field intensity. However, convection does exceed neutral thermal speeds, and increases steeply as the magnetic field weakens with altitude, such that higher altitude plasmas on the same flux tubes approach or exceed the gravitational escape speed, especially when they are picked up from rest with a factor of two increase in gyration velocity. to form the ring-beam. These parameters are illustrated for a particular choice of ionospheric conditions in Figure 1. Here the Poynting Flux at 4000 km altitude has been set to 100 mW/m^2 so the system is driven to the upper limit of the range observed in the Strangeway [2005] study.

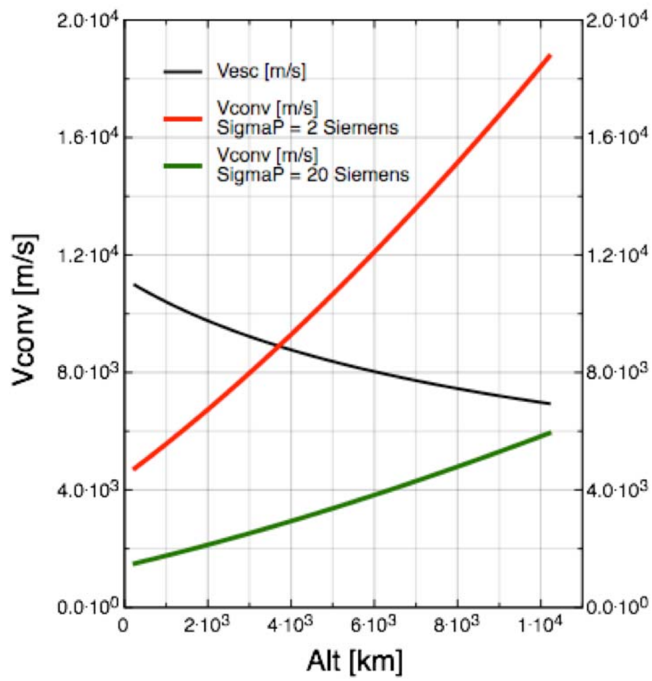

Figure 1. Altitude dependence of convection speed and escape speed, for Poynting Flux of 100 mW/m^2 at 4000 km altitude.

The increase in the convection speed with altitude is in part the origin of the centrifugal acceleration effect [Horwitz et al., 1994]. As shown by those works, plasma flowing along rapidly convecting magnetospheric flux tubes will gain escape energy from the convection electric field at some altitude, and will continue to be accelerated to very high altitudes as perpendicular energy is acquired from the convection electric field. This can be understood as a result of the curvature and polarization drift of convecting particles, along the convection electric field, owing to its variation in the frame of the particles. Ions gain equal amounts of perpendicular and parallel energy, essentially equal to the convection speed at any altitude, less gravity effects [Horwitz et al., 1994]. Escape or outflow occurs for those parts of the distribution that have a transverse velocity exceeding the local escape speed. Thus, a ring beam distribution will move upward and have its transverse energy enhanced proportional to the local convection speed, gaining parallel energy as it evolves upward.

Conductance

The ionosphere is embedded within the thermospheric gas. As expressed by Alfvén's frozen-in flux theorem, the geomagnetic field seeks to enforce ionospheric convection matching magnetospheric convection, but the plasma motion is opposed by drag owing to collisions with the thermospheric gas, demagnetizing the ions and allowing transverse current to flow. Maxwell stresses to drive ionospheric plasma flow and retard magnetospheric flow, are transmitted by electric currents, powered by the Poynting energy flux from magnetosphere to ionosphere.

We refer to conductance distributions from Ridley [2004] as representative. That study summarizes contributions to global conductance from sunlight and the auroral zone, as well as their effects on magnetospheric circulation. We consider a range of $\sum P$ from 2-20 Siemens, which is representative of the entire dayside region and polar cap under a wide range of conditions. By inference, convection speeds will be correspondingly lower in the low latitude dayside or night time auroral zone, but

Poynting flux may be larger and more variable there, with opposite effects on the charge exchange frictional effect.

Thermalization

In practice, ring beams should be difficult to observe, consistent with their rapid diffusion into hot distributions. Any velocity distributions with positive df(**v**)/dv (free energy) quickly grow waves that diffuse away the free energy feature. One expects instead to observe distributions that are near marginal stability. In this section we highlight selected pieces of evidence for this thermalization and measures of its results, as well as theoretical models of the process.

Plasma Observations: St-Maurice [1976] reported plasma analyzer observations of the ring feature, but never with a pronounced minimum at zero velocity. The ratio of the ring to thermal speed never exceeded 1.5, even when conditions indicated a ring to thermal ratio of 2 to 3 or more. This is consistent with rapid thermalization of the ring beam feature by unstable waves. Space and time variability of the ionosphere is also a significant problem for these observations that makes it difficult to capture a ring beam feature [Moore et al., 1996]. There have been some high altitude observations suggestive of extended ring beam features in the topside ionosphere [Moore et al., 1985], but they are exceedingly rare.

A great many observations have been made of transversely accelerated or heated ions, and their close relatives, ion conics [Moore and Horwitz, 2007]. The transverse or conic feature indicates that energization is a much faster process than pitch angle diffusion in the auroral ionosphere. Figure 2 shows observations by the Swedish

Freja spacecraft [André et al., 1994]. Here the energy distribution resembles a power law with a core that is exponential in velocity. The authors simulated the effect of the ambient wave populations observed by Freja and concluded that those waves would heat cold ions so as to produce the observed hot tail distributions. The question left open is that of the source of the waves.

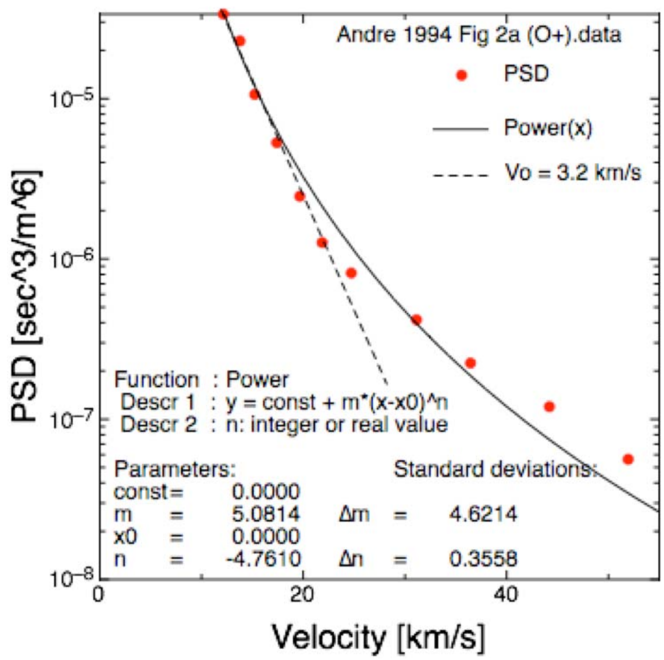

Figure 2. A representative example of the energy distribution of transversely accelerated ions [After André et al. 1994], from the Freja mission at about 1700 km altitude over the auroral zone.

Wave Observations: Plasma waves in the auroral ionosphere may be generated locally or propagated in from remote sources. Ion cyclotron waves are the most directly coupled with transverse motions of ions. At lower frequencies, transverse Alfvén waves, propagating in from higher altitude, have been associated with strong ion outflows by Tung et al., [2001] and Chaston et al., [2006]. Local wave growth owing to a ring beam feature was described by Post and Rosenbluth [1966], but in the context of a loss cone instability. Such waves are commonly observed in the topside ionosphere under conditions of strong convection [St-Maurice, 1979].

Non-Thermal IS Radar Echoes: Several reports of incoherent scatter radar echo spectra have been interpreted as the result of backscatter from plasmas with a toroidal or ring beam shaped velocity distribution [Suvanto et al., 1989; Kinzelin et al., 1992]. The distributions are oriented with the ring axis parallel to the local magnetic field, so that they can only be detected when the plasma is viewed along a line of sight that makes a sufficiently large angle with the local magnetic field, exceeding 20˚. This demonstrates there are regions where ring beam velocity distributions, or thermalized versions of them, are detectable to radars observing the topside ionosphere under rapid convection.

Interstellar Gas and Comets: The “ion pick up” process [Bogdan et al., 1991] has been observed to create ring beams usually observed as shell distributions in interplanetary space, from freshly ionized cold gas atoms. Near comets, plasma analyzers encounter greatly enhanced ion-neutral interactions that produces pick up ion (PUI) populations [Neugebauer et al., 1990], as well as thermalized hot tails attributable to them [Mukai, 1986; Richardson et al. 1987]. This has permitted detailed studies of the ring beam thermalization process under conditions within the coma at varying distance from cometary nucleii. Considerable theoretical work has been done to understand the plasma waves created by the ring beam instability [Lee and Gary, 1991], and to understand their thermalizing effects on the ring beams [Puhl et al,. 1993].

Theoretical concepts: In the weak magnetic fields and high speed plasma flows of interplanetary space and cometary comae, quasilinear theory describes diffusion along circles centered on the dominant wave phase speed, V_A. This emphasizes pitch angle diffusion along circles centered at +/- V_A , that is, near the origin in velocity space, relative to the ion ring beam. It leads to formation of a bi-spherical shell distribution, with little energy diffusion. Deeper in a cometary coma, plasma flow velocities decrease until they are comparable to and eventually much smaller than V_A. Then the diffusion surfaces are centered at relatively large values of +/- V_A. Moreover, dispersive ion cyclotron waves become important, with non-circular diffusion paths [Isenberg and Vasquez, 2007]. Transverse energy diffusion then becomes more important than pitch angle diffusion. The observed hot tails have been simulated using a pure diffusive formulation with the diffusion coefficient treated as a fitting parameter [Puhl et al. 1993]. The problem was considered from outermost fringes to deep within the inner coma, where velocities are much smaller than V_A, and charge exchange and collisions had to be included. The simulated hot tail is of power law form overall, but is exponential (in v) within the near tail at low energies. The e-folding energy of the hot tail is equal to double the local convection speed of the ions through the neutrals, for small velocities, as shown by their figure 6b.

Liu, et al. [2005] reported on quasilinear thermalization of ring beam distributions downstream of plasma shocks, including cases where the plasma velocity is less than V_A. They found the approximately bi-spherical diffusion surfaces to be consistent with perpendicular temperature anisotropy (Tperp/Tparl) as high as 2.5. They conceded that observations show even higher anisotropies with more extended energy distributions than predicted from quasilinear theory. They also note intermittency in the observed waves, concluding that turbulence and nonlinearity are present that is not accounted for by their model.

The observations and theoretical work summarized above suggest the conclusion that ion ring beam distributions are rapidly thermalized. In the low speed case, a transverse hot power law tail is quickly formed as a result, with a low speed core having an e-folding speed equal to double the local speed of ion convection through the neutral gas. We adopt the observed distribution as a working distribution form, even though it is not yet produced by a first principles theory.

Oxygen Escape Flux

We can now estimate the O^+ escape flux dependence on Poynting flux as follows: The convection electric field, consistent with the ionospheric conductance, determines the convection speed of the flux tube, and its altitude dependence above the sensible drag medium. The resulting topside ring beam is assumed to be thermalized into a transverse exponential tail with e-folding speed taken to be double the local convection speed. The amount of the tail distribution that extends above the local escape speed is computed as the fraction of the local density that will escape. The e-folding speed of the tail is also taken to indicate the parallel velocity with which this escape will proceed. Thus the fraction of the limiting flux (taken to be 2 x

10^{10} cm^{-2} sec^{-1} for O^+) that will escape is estimated as the product of the convection speed with the fraction of the tail density that extends above the escape speed.

Eqn 1. F_E = Flimit * (Vconv/Vesc) * exp(-Vesc/Vconv)

The results of this integration are shown in Figure 3 for a range of ionospheric conductance. For comparison, a plot of the Strangeway et al. [2005] serves as background.

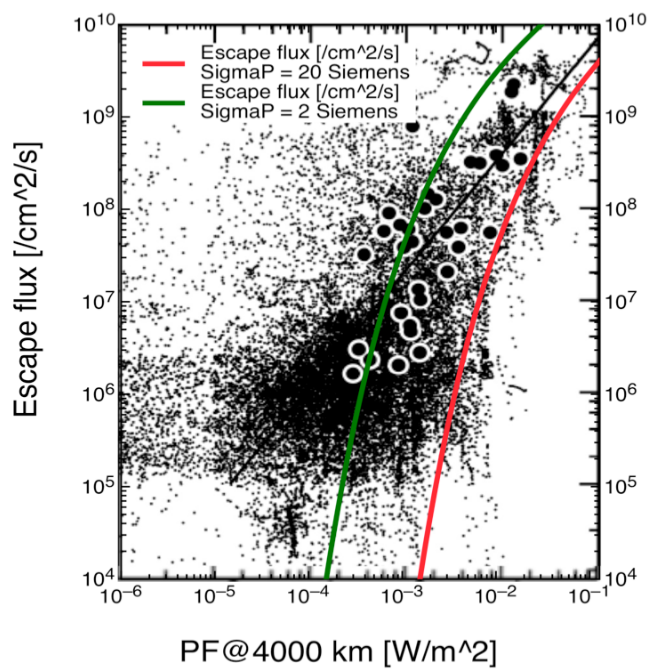

Figure 3. Estimate of escape flux dependence upon Poynting flux at 4000 km altitude. Results from Strangeway et al., [2005] (FAST O+) are shown for comparison.

Discussion

The calculation used here assumes a fixed vertical distribution of ionospheric plasma, whereas that density is strongly influenced by lower altitude Joule and precipitation heating, and thus by the Poynting flux. These effects are to some degree accommodated in the conductance value range we have used, because conductance is essentially proportional to density.

The results derived here suggest that three processes are significant in ionospheric escape: i) Joule/frictional ion heating and electron precipitation thermal heating of the collisional F-region, ii) charge exchange friction, with ring beam velocity distributions and their thermalization in the topside ionosphere; and iii) centrifugal acceleration in the high topside. All three processes respond to the speed of convection and thus to the amount of power (Poynting flux) available from reservoirs in the magnetosphere or from the solar wind where it is directly linked. But a crucial role is played by process ii), charge exchange friction, in that plasma escape is throttled by the degree to which ions are heated enough to be free of gravity. The electron and ion heating processes controlling flux operate like conductances in series. Thus, we conclude that the lack of either can effectively cut off outflow flux and that their combined effect is proportional to their product.

This result provides a theoretical basis for the empirical scalings of Strangeway [2005]. Strangeway has also investigated the empirical association of ion heating and outflow with electromagnetic wave energy (AC Poynting) flux and shown there to be a high correlation [personal communication], with a similar high correlation between DC energy flux and AC or wave energy flux. The question of how much wave energy is locally generated and how much propagates in from external processes is interesting and bears study, and it seems likely that both will contribute appreciably to heating and outflow, but perhaps in different locales, under different conditions.

Conclusions

We have shown that charge exchange friction, which creates ring beam velocity distributions and associated pickup ion processes, including energy diffusion, imparts escape energies to a portion of the topside ion velocity distribution that increases steeply with Poynting flux and the resultant speed of driven ion-neutral convection. The resultant dependence on the Poynting flux of electromagnetic energy from the magnetosphere tracks the exponential tail that has been observed.

Acknowledgments

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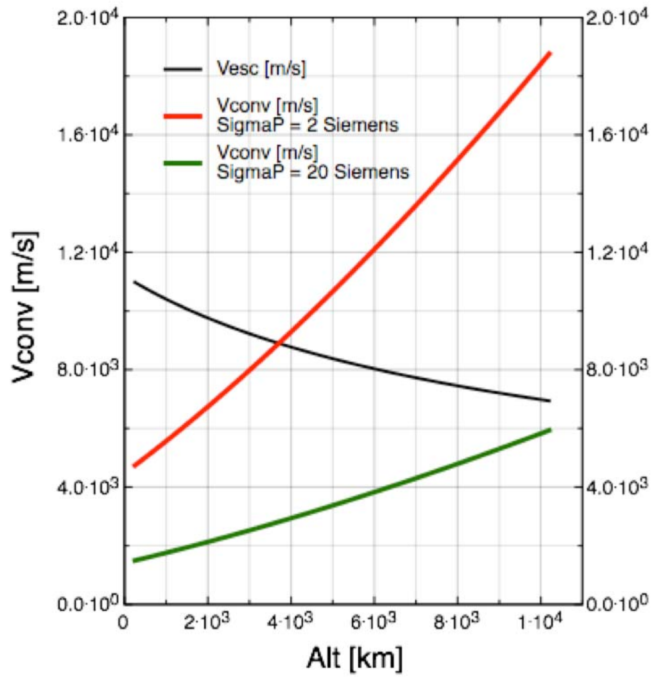
3 # Figures



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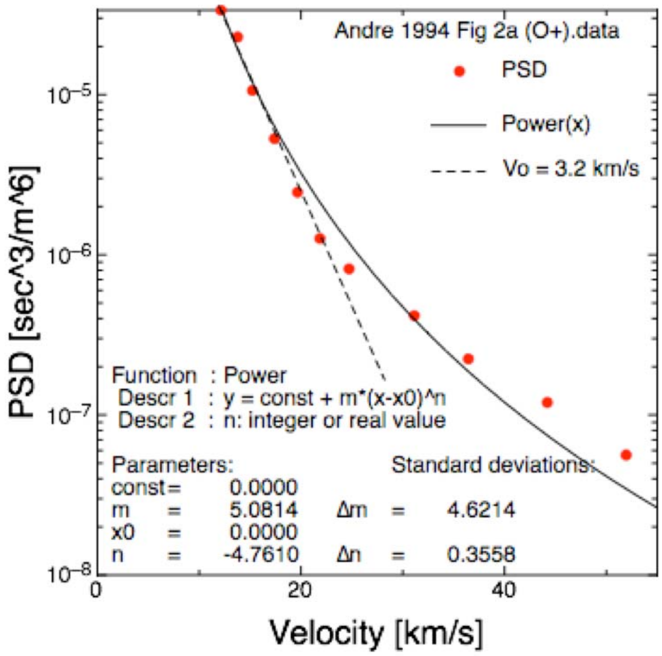
5 Figure 1. Altitude dependence of convection speed and escape speed, for Poynting

6 Flux of 100 mW/m^2 at 4000 km altitude.



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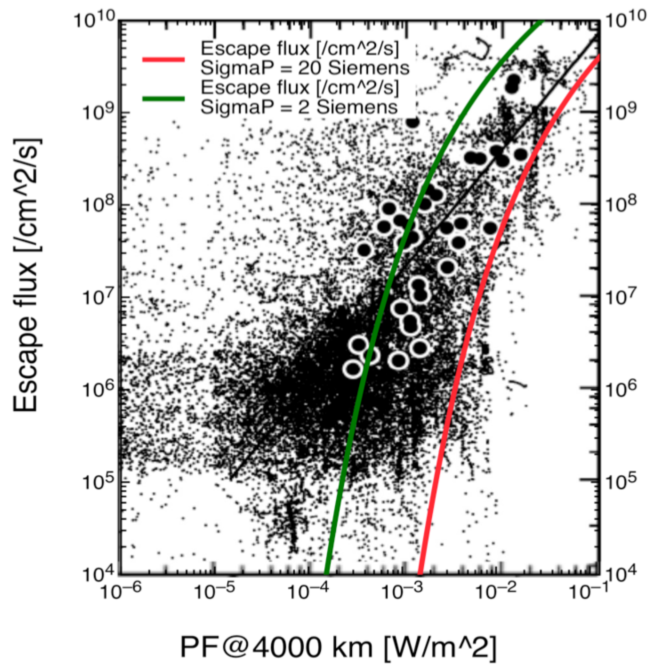

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